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ON A METHOD OF PROPULSION OF PROJECTILES BY MEANS OF EXTERNAL NUCLEAR EXPLOSIONS
PART I

by

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NUCLEAR PROPULSION

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NUCLEAR PROPULSION

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ABSTRACT

Repeated nuclear explosions outside the body of a projectile are considered as providing means to accelerate such objects to velocities of the order of 10^6 cm/sec. A few schematic calculations are presented, showing the dependence of the mass ratios ("propellant" to the final mass), accelerations, etc., on the various free parameters entering in this scheme.

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1. INTRODUCTION

It is the purpose of this report to summarize certain considerations and proposals, some of which originated as long as ten years ago, and to discuss additional ideas concerning the attempt to attain velocities in the range of the missiles considered for intercontinental warfare and even more perhaps, for escape from the earth's gravitational field, for unmanned vehicles.

The methods most frequently proposed for obtaining such vehicles involve expulsion of material at high velocity from rocket motors. This ejected material is heated in the rocket itself, either by a chemical reaction, or, in more recent schemes, by nuclear reactors. (Cf., e.g., LAMS-1870 and LAMS-1887.) In both cases there is a severe limitation on motor temperature and thus also on the velocity of material ejected. The well-known exponential rocket formula* then demands impractical mass ratios for the attainment of final velocities V_f in the desired ranges, and multi-stage vehicles become necessary. The advantage of the nuclear rocket of this kind over the chemical type lies paradoxically not so much in its potentially enormous power source, which is limited by chamber temperature T to much the same range as chemical motors, but in its ability to use hydrogen as propellant, with

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* M_o/M_f = mass-ratio = $\exp(V_f/I)$, I = specific impulse.

molecular weight μ lower than the average of chemical reaction products (cf. LA-714, page 8), thus permitting operation at higher specific impulse, which is a function of $\sqrt{T/\mu}$.

The scheme proposed in the present report involves the use of a series of expendable reactors (fission bombs) ejected and detonated at a considerable distance from the vehicle, which liberate the required energy in an external "motor" consisting essentially of empty space. The critical question about such a method concerns its ability to draw on the real reserves of nuclear power liberated at bomb temperatures without smashing or melting the vehicle.

General proposals of this sort were first made by S. Ulam in 1946, and some preliminary calculations were made by F. Reines and S. Ulam in a Los Alamos memorandum dated 1947. More recently, an additional idea was advanced, which consists in placing between each bomb and the rocket a "propellant" consisting of water or some plastic, which will be heated by the bomb, and which will propel the vehicle during its subsequent explosive expansion. Some of the advantages of this proposal will be mentioned in the final section.

In any such device, one of the principal difficulties is the heating of the rocket by the propellant. We seem to encounter a situation in which the base of the rocket will be, periodically, at one second intervals, in the proximity of a very hot gas for durations of about one millisecond each. Study of the effects of such a variable wall temperature on various materials will be made, and reported on subsequently.

The most recent idea is that the use of a sufficiently powerful magnetic field shielding the base of the rocket will have the effect of reflecting the (ionized) atoms of the hot propellant gas before they reach the rocket, thus avoiding heating of the base and incidentally gaining a factor on momentum transfer. It is hoped that this possibility also may be investigated at least schematically and reported on in Part II. However, there appear to be many difficulties in such a study, involving the reaction of a plasma to the magnetic field. Whether the field strength required is impractically large remains to be seen. There is, it seems, the possibility of the formation of a powerful plasma current at the base of the rocket and a pinch effect, which may mean that the magnetic field becomes compressed to a smaller volume and the magnetic pressure considerably increased.

2. KINEMATICS

In order to gain some quantitative insight into the elements of such a system, we propose to adopt a particular set of assumptions and to study numerically the effect of variation of parameters. The Eqs. (1-7) which follow are obviously highly tentative and subject to many questions here unresolved.

The vehicle is considered to be saucer-shaped, of diameter about 10 meters, sufficient at any rate to intercept all or most of the exploding propellant. Its final mass M_f is perhaps 12 tons, which must cover structure, payload, instruments, storage for propellant and bombs, and, if required, apparatus for maintaining the magnetic field. The initial mass M_o of the vehicle exceeds this by the mass of bombs and propellant.

The bombs are ejected at something like one second intervals from the base of the rocket and are detonated at a distance of some 50 meters from the base. Synchronized with this, disk-shaped masses of propellant are ejected in such a way that the rocket-propellant distance is about 10 meters at the instant the exploding bomb hits it. The propellant is raised to high temperature, and, in expanding, transmits momentum to the vehicle. The final velocity V_f is attained after N (~50) such explosions.

We regard now the i-th stage of the process. From the rocket, traveling at velocity V^{i-1} with respect to the earth, are ejected first the i-th bomb (mass m_B) and then the i-th mass of propellant m_P^i at some small velocity v_o relative to the rocket. It is supposed that, upon detonation, a certain fraction σ of the mass of the bomb collides inelastically with the ejected propellant mass. This fraction could be made, in our case, perhaps as much as 1/10, which is considerably more than the factor given by the solid angle. This could probably be achieved by a suitable distribution of the mass of the tamper surrounding the core of the bomb. In this way, a larger fraction of the mass of the bomb would hit the propellant. (It is easy to make the distribution of the mass involved in the bomb explosion nonisotropic;

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the energy distribution is probably essentially isotropic.) If v_B^i is the average velocity of explosion of the bomb in the sector reaching the propellant, we have

$$\sigma m_B(V^{i-1} - v_o + v_B^i) + m_P^i(V^{i-1} - v_o) = (\sigma m_B + m_P^i)\, V_P^i,$$

where V_P^i is the velocity relative to the earth of the center of mass of the combined system $(\sigma m_B, m_P^i)$. If we introduce a velocity v_P^i by means of the relation

$$V_P^i = V^{i-1} - v_o + v_P^i$$

we obtain

$$\sigma m_B\, v_B^i = (\sigma m_B + m_P^i)\, v_P^i\ . \tag{1}$$

The excess kinetic energy in this transfer is supposed to appear initially as thermal energy H^i in the propellant

$$H^i = \tfrac{1}{2}\sigma m_B(v_B^i)^2 - \tfrac{1}{2}(\sigma m_B + m_P^i)(v_P^i)^2\ . \tag{2}$$

It is assumed that about half of this heat H^i reappears in kinetic energy of expansion of the propellant, with an expansion velocity v_E relative to its own center

$$\tfrac{1}{2}\, H^i = \tfrac{1}{2}(\sigma m_B + m_P^i)(v_E^i)^2. \tag{3}$$

We assume, arbitrarily, that in the expansion of the propellant, one half of its internal energy becomes converted to kinetic energy of

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expansion. This fraction depends obviously on the distance d and is, in our case, higher.

In our schematic computation we prefer to adopt this much too conservative value.

We may consider that the upper and lower halves of the exploding propellant travel with average velocities

$$v_P^i \pm v_E^i,$$

respectively. Now Eqs. (1), (2), (3) show that

$$(v_E^i)^2 = \frac{1}{2}\left(\frac{m_P^i}{\sigma m_B}\right)(v_P^i)^2$$

and since, in all cases we consider, $m_P^i > 2\sigma m_B$, we have $v_E^i > v_P^i$. Thus $V_P^i - v_E^i = V^{i-1} - v_o + v_P^i - v_E^i < V^{i-1}$, and the lower half of the exploding propellant will not reach the rocket.

The momentum conservation equation for the rocket and upper half of the propellant should read

$$\frac{1}{2}(\sigma m_B + m_P^i)\,(V^{i-1} - v_o + v_P^i + v_E^i) + M^i\,V^{i-1} =$$

$$\frac{1}{2}(\sigma m_B + m_P^i)\,\left(V^{i-1} - (-v_o + v_P^i + v_E^i)\right) + M^i\,V^i,$$

or, simplifying,

$$\frac{1}{2}(\sigma m_B + m_P^i)\cdot 2(-v_o + v_P^i + v_E^i) = M^i\,\Delta_i V,$$

where M^i is the present mass of the rocket, and $\Delta_i V$ is the i-th increment in its velocity relative to the earth. This assumes total reflection of the propellant. To allow for side effects and imperfect reflection, we use the equation

$$\frac{1}{2}(\sigma\, m_B + m_P^i)\ (v_P^i + v_E^i) = M^i\, \Delta_i\, V. \tag{4}$$

Finally, we assume the time $\Delta_i t$ for the i-th acceleration to be

$$\Delta_i t = 2d\Big/(v_P^i + v_E^i) \tag{5}$$

where d is the distance from propellant to rocket. The i-th acceleration is thus

$$\alpha_i = \Delta_i V\Big/\Delta_i t. \tag{6}$$

There are two cases of mathematical simplicity which we outline, and for which we include some numerical examples. (Tables 1 and 2 for the cases 1 and 2, respectively.)

<u>Case 1. Constant Acceleration</u>

We take as independent parameters:

V_f the final velocity

M_f the final mass of the rocket

N the number of stages (bombs)

α the acceleration at each stage (assumed constant)

d distance from propellant to rocket

m_B mass of each bomb

σ fraction of m_B hitting propellant

and show how all other parameters may be expressed in terms of these.

Thus each change in velocity will be

$$\Delta_i V = V_f/N \tag{7}$$

over a time interval

$$\Delta_i t = \Delta_i V/\alpha = V_f/\alpha N. \tag{8}$$

The propelling velocity $v_P^i + v_E^i \equiv \omega^i$ is thus

$$\omega_i = 2d/\Delta_i t = 2\alpha N d/V_f \;. \tag{9}$$

We now consider Eq. (4), setting

$$C = (1 - \sigma)m_B \tag{10}$$

and $m_i = m_B + m_P^i$, the total ejected i-th mass. Thus (4) becomes

$$m_i - C = k\left\{M_o - \sum_{j=1}^{i} m_j\right\} \tag{4*}$$

where

$$k = 2\Delta_i V/\omega_i = \frac{1}{\alpha d}\left(\frac{V_f}{N}\right)^2 \tag{11}$$

and M_o is the initial mass of the rocket.

Writing the equation (4*) for $i + 1$ and subtracting shows that $m_{i+1} = m_i\rho$ where

$$\rho = \frac{1}{1 + k}\;. \tag{12}$$

Thus $m_i = m_1\rho^{i-1}$, $i = 1, 2, \ldots, N$. We determine M_o and m_1 as follows. Substituting $\sum_{j=1}^{i} m_j = m_1(1 - \rho^i)/(1 - \rho)$ into (4*) shows that

$$m_1(1 + k) = k\, M_o + C,$$

while, by definition,

$$M_o - M_f = \sum_{j=1}^{N} m_j = m_1(1 - \rho^N)\Big/(1 - \rho) = \frac{m_1}{k}(1 + k)(1 - \rho^N).$$

Eliminating M_o between these two relations yields

$$m_1 = (k\, M_f + C)(1 + k)^{N-1} \tag{13}$$

and so

$$M_o = \Big[m_1(1 + k) - C\Big]\Big/k. \tag{14}$$

Thus we have trivially the i-th mass:

$$m_i = m_1\, \rho^i, \tag{15}$$

the mass ratio:

$$\text{M.R.} = M_o\big/M_f, \tag{16}$$

the total expelled mass:

$$T = M_o - M_f, \tag{17}$$

the total bomb mass:

$$M_B = N\, m_B \tag{18}$$

the total propellant mass:

$$M_P = T - M_B \tag{19}$$

and the i-th mass of propellant:

$$m_P^i = m_i - m_B. \tag{20}$$

Now, solving equations (1), (2), and (3) for v_P^i and v_E^i in terms of v_B^i, we get

$$v_P^i = \sigma m_B \;\; v_B^i\big/m_i - C \tag{21}$$

and

$$v_E^i = \frac{1}{m_i - C}\sqrt{\frac{\sigma m_B\, m_P^i}{2}} \cdot v_B^i.$$

Substitution into

$$v_E^i + v_P^i = \omega \tag{22}$$

yields

$$v_B^i = \omega(m_i - C) \Big/ \left\{ \sigma m_B + \sqrt{\frac{\sigma m_B m_P^i}{2}} \right\} \tag{23}$$

whence the values of v_P^i and v_E^i may now be obtained, using (21) and (22), respectively.

Thus all parameters are determined in terms of the fundamental set V_f, M_f, N, α, d, m_B, σ. It is interesting to note that the mass ratio

$$\text{M.R.} = \frac{m_1(k + 1) - C}{m_1(k + 1)\rho^N - C}$$

is (approximately in general and exactly when $C = 0$)

$$(1 + k)^N$$

where $k = \frac{1}{\alpha d}\left(\frac{V_f}{N}\right)^2$, which indicates the extreme sensitivity of the mass ratio to α, N, d, and especially to V_f, in the constant acceleration case.

A rough indication of the energy of the i-th bomb is given by the $k_B^i = \frac{1}{2} m_B \left(v_B^i\right)^2$ included in the tables. The actual yield of each bomb is several times greater since we assumed a special shaping of the tamper to concentrate as much as possible the mass, but not the energy of the exploding bomb, towards the propellant.

Table 1 is intended to show how the various factors in the problem depend on the initial parameters N, α, d and m_B. None of the twelve "problems" is intended as an optimum case. It may be noted that problems

1 and 2 with $V_f = .7 \times 10^6$ are included for the sake of comparison with various intercontinental ballistic missiles schemes. It should be noted that our mass ratios are considerably less than those contemplated in such cases, while the accelerations are very much more ($\sim$10,000 g's), lasting for periods of about 1 millisecond each. One also notes that the bombs are rather "small" (10^{19} - 10^{20} ergs).

TABLE 1

(c.g.s. units)

Problem #	1	2	3	4	5	6	7	8	9	10	11	12
$V_r \times 10^{-6}$	.7	.7	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
$M_r \times 10^{-6}$	12	12	12	12	12	12	12	12	12	12	12	12
N	40	80	30	30	30	40	40	40	60	100	100	100
$\alpha \times 10^{-6}$	20	10	100	50	20	30	20	20	10	8	8	5
$d \times 10^{-2}$	6	10	6	10	6	10	6	10	10	10	10	10
$m_B \times 10^{-6}$	.5	.2	.5	.5	.5	.3	.5	.3	.3	.3	.2	.3
σ	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
$\Delta V \times 10^{-6}$	.0175	.00875	.04	.04	.04	.03	.03	.03	.02	.012	.012	.012
$\Delta t \times 10^{3}$	.875	.875	.4	.8	2.0	1.0	1.5	1.5	2.0	1.5	1.5	2.4
$\omega \times 10^{-6}$	1.37	2.29	3.00	2.50	.60	2.00	.80	1.33	1.00	1.33	1.33	.833
k	.0255	.0077	.0267	.032	.133	.030	.075	.045	.04	.018	.018	.0288
$m_1 \times 10^{-6}$	2.02	.498	1.65	2.08	76.5	2.00	22.7	4.51	7.59	2.84	2.32	10.2
$m_N \times 10^{-6}$	.756	.272	.770	.834	2.05	.63	1.35	.810	.750	.486	.396	.616
$M_0 \times 10^{-6}$	63.6	42.1	46.8	53.0	648.	59.5	319.	98.7	190.5	146.	121.	356.
M.R.	5.3	3.5	3.9	4.4	54.0	5.0	26.6	8.2	15.9	12.1	10.1	29.7
$T \times 10^{-6}$	51.6	30.1	34.8	41.0	636.	47.5	307.	86.7	178.5	134.	109.	344.
$M_B \times 10^{-6}$	20	16	15	15	15	12	20	12	18	30	20	30
$M_p \times 10^{-6}$	31.6	14.1	19.8	26.0	621	35.5	287.	74.7	160.5	104	89.	314
$m_p^1 \times 10^{-6}$	1.52	.298	1.15	1.58	76.0	1.70	22.2	4.21	7.29	2.54	2.12	9.9[illegible]
$m_p^N \times 10^{-6}$	.256	.0719	.270	.334	1.55	.33	.85	.51	.45	.186	.196	.31[illegible]
$v_B^1 \times 10^{-6}$	8.78	9.75	16.4	16.4	32.0	18.2	22.4	20.1	20.3	15.2	17.2	20.0
$v_B^N \times 10^{-6}$	3.23	4.49	7.27	6.79	3.88	7.17	3.68	6.13	4.28	3.48	4.48	2.92
$k_B^1 \times 10^{-18}$	19.3	9.51	67.5	67.1	255.	49.8	125.	60.5	61.8	34.8	29.6	59.8
$k_B^N \times 10^{-18}$	2.60	2.01	13.2	11.5	3.77	7.72	3.38	5.63	2.75	1.81	2.01	1.28
$v_p^1 \times 10^{-6}$	.280	.613	.682	.503	.0210	.317	.0504	.142	.0832	.178	.161	.0601
$v_p^N \times 10^{-6}$	.527	.977	1.14	.884	.122	.598	.204	.341	.268	.483	.415	.253
$v_E^1 \times 10^{-6}$	1.09	1.67	2.32	2.00	.579	1.68	.750	1.19	.917	1.16	1.17	.773
$v_E^N \times 10^{-6}$	.844	1.31	1.87	1.62	.478	1.40	.596	.993	.733	.850	.919	.580

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Case 2. Constant Mass

In this case, which closely corresponds to the usual rocket assumption, we take as independent parameters M_f, N, d, m_B, σ, and now m_P, v_B (assumed constant) instead of α and V_f.

Thus we have for the mass expelled at each stage:

$$m = m_B + m_P, \tag{24}$$

the total bomb mass:

$$M_B = N\, m_B, \tag{25}$$

and the total propellant mass:

$$M_P = N\, m_P, \tag{26}$$

the total mass expelled:

$$T = M_B + M_P, \tag{27}$$

the initial rocket mass:

$$M_o = M_f + T, \tag{28}$$

and the mass ratio:

$$M.R. = M_o/M_f. \tag{29}$$

Since v_B is given, we find from Eq. (1) that

$$v_P = \sigma m_B\, v_B/(\sigma m_B + m_P), \tag{30}$$

while Eqs. (2) and (3) show that

$$H = \frac{1}{2}\, \sigma m_B\, v_B^2\, (m_P/\sigma m_B + m_P) \tag{31}$$

and

$$v_E = \sqrt{H/(\sigma m_B + m_P)}. \tag{32}$$

Hence we again have a constant propelling velocity given by

$$\omega = v_P + v_E. \tag{33}$$

The "rocket equation" (4) now becomes

$$L = \frac{1}{2}(\sigma\, m_B + m_P)\omega = M^i\ \Delta_i\ V,$$

the left side being a known constant, and $M^i = M^o - im$ being a known function of $i = 1, \ldots, N$. Hence we can compute the i-th increment of velocity

$$\Delta_i\ V = L \big/ M^i \tag{34}$$

and the velocity after i stages:

$$V_i = \sum_{j=1}^{i} \Delta_j\ V. \tag{35}$$

In particular the final velocity is

$$V_f = V_N = \sum_{j=1}^{N} \Delta_j\ V. \tag{36}$$

The time $\Delta_i\ t$ is given by the constant

$$\Delta_i t = 2d/\omega \tag{37}$$

and hence we have the i-th acceleration

$$\alpha_i = \Delta_i V \big/ \Delta_i t. \tag{38}$$

In particular,

$$\alpha_{min} = \alpha_1 = \left(\frac{L\,\omega}{2\ d}\right)\Big/(M_o - m) \tag{39}$$

and

$$\alpha_{max} = \alpha_N = \left(\frac{L\,\omega}{2\ d}\right)\Big/M_f. \tag{40}$$

In analogy with the usual rocket equation, our Eq. (34) might be written

$$\left(\frac{L}{m}\right) m = M^{i} \Delta_i V$$

or, letting $\beta = L/M = \frac{1}{2}\left(\frac{\sigma m_B + m_P}{m}\right) \cdot \omega$

$$-\beta \, dM = M \, dV$$

whence $\frac{dM}{M} = -\beta^{-1} \, dV$

and $\ln \frac{M_o}{M} = \beta^{-1} V$

or $\frac{M_o}{M_f} = e^{V_f/\beta}$,

which affords a rough estimate of V_f, namely

$$V_f \sim \frac{L}{m} \ln(\text{M.R.}).$$

In Table 2, Problem #4' is intended to be an analogue of Problem #4 of Table 1, while Problem #12' is intended as a companion to Problem #12 of the former table. It may be noted that in order to duplicate the performance of a given rocket of constant acceleration α by the second method, one requires accelerations whose average is $\sim\alpha$ and which, therefore, individually greatly exceed α in the final stage. It may be that the method of Case 1, although unorthodox, has advantages in this sense which might justify the use of bombs of variable yield.

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TABLE 2

(c.g.s. units)

Problem #	4'	12'
$M_f \times 10^{-6}$	12	12
N	30	100
$d \times 10^{-2}$	10.	10.
$m_B \times 10^{-6}$	.5	.3
σ	.1	.1
$m_p \times 10^{-6}$	1.	3.
$v_B \times 10^{-6}$	10.	10.
$M_B \times 10^{-6}$	15	30
$M_p \times 10^{-6}$	30	300
$T \times 10^{-6}$	45	330
$M_o \times 10^{-6}$	57	342
M.R.	4.75	28.5
v_p	.476	.0990
$k_B \times 10^{-18}$	25	15
$v_E \times 10^{-6}$	1.51	.700
$\omega \times 10^{-6}$	1.98	.799
$L \times 10^{-12}$	1.041	1.211
$\Delta t \times 10^{3}$	1.0	2.5
$\Delta_1 V \times 10^{-6}$	.0188	.00357
$^*\Delta_N V \times 10^{-6}$	.0868	.1009
$\alpha_1 \times 10^{-6}$	18.8	1.43
$\alpha_N \times 10^{-6}$	86.8	40.4
$v_f \times 10^{-6}$	1.12	1.28
$(\frac{L}{m} \ln \text{M.R.}) \times 10^{-6}$	1.08	1.23

*The complete $\Delta_1 V$ table is not included.

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3. REMARKS

1. The mass of each fission bomb is assumed to be of the order of 500 kg, including tamper and explosive. Since these bombs are of small yield and many of them are required, they might be of hydride composition. Certainly a disadvantage of our scheme is its wastefulness of fissionable material.

2. The figure of 12 tons for the final mass of the projectile was assumed arbitrarily in our computations. Actually increasing this number with a proportional increase in the mass of the propellant is very advantageous since the mass of the bombs need hardly be increased even though their yields can be made considerably greater. Thus with, say, 20 tons for the vehicle the mass ratio will be more favorable.

3. Assuming ~ 1 second intervals between explosions, the total duration of the process will be less than 100 seconds, and the resulting loss of velocity due to the earth's gravitational pull will not exceed 10^5 cm sec^{-1}. Thus the velocity V_f of Section 2 should be taken as the actual desired final velocity plus 10^5. This explains our use of $V_f = 1.2 \times 10^6 = 1.1 \times 10^6 + .1 \times 10^6$.

4. The accelerations of the order of 10,000 g are certainly large, and must be rather uniform over the entire structure or breakage is inevitable. The question of the necessary strength for our structure under such accelerations has not been studied. Shock heating in these accelerations is believed to be small.

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5. The problem of predetonation of remaining bombs by neutron flux from previously exploded ones must be considered. Strong source bombs and suitable shielding should overcome this difficulty. One should also consider the heating of the vehicle by neutrons and γ-rays. Solid angle considerations insure that this effect will be small.

6. The propellant could be made of a solid material fabricated in N sheets which are placed at the bottom of the projectile. They are detached one by one and expelled to the desired distance. They could be separated by very thin ceramic layers. The placing of the propellant at the bottom of the structure has the advantage that the problem of heating of the permanent structure is attenuated. After each explosion only a small fraction of the next sheet of the propellant would be lost by evaporation and melting.

7. The problem of heating by the propellant and the possible avoidance of this difficulty by the use of magnetic fields have yet to be studied and will be reported in Part II as indicated previously.

8. The whole scheme presupposes elevation of the entire structure beyond the earth's atmosphere by a chemical booster rocket. On the other hand, for the first few explosions we could use air as the propellant with a resultant gain in our mass ratio and with smaller accelerations.

9. We have assumed that the expansion of the thin propellant layer will be essentially perpendicular to its disk surfaces. The